

DIFFERENTIAL CHARGE PUMP

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BACKGROUND OF THE INVENTIONField of the Invention

[0001] The invention relates to charge pumps, and in particular, to an accurate and stable differential charge pump.

Related Art

[0002] A differential charge pump converts a differential signal into an output voltage by charging a capacitor (or capacitors). Fig. 1 shows a conventional differential charge pump 100 that includes: switches S(A), S(B), S(C), and S(D); current sources CS(A), CS(B), CS(C), and CS(D); and a charging capacitor 110.

[0003] Switch S(A), current source CS(A), current source CS(B), and switch S(B) are connected in series between supply voltage VDD and ground, thereby forming a first control branch B(A). Similarly, switch S(C), current source CS(C), current source CS(D), and switch S(D) are connected in series between supply voltage VDD and ground, thereby forming a second control branch B(B).

[0004] First control branch B(A) includes a terminal T(A) at the junction between current sources CS(A) and CS(B), while the second control branch B(B) includes a terminal T(B) at the junction between current sources CS(C) and CS(D). Capacitor 110 is connected between terminals T(A) and T(B), thereby allowing a differential output voltage VDIFF across capacitor 110 to be read via terminals T(A) and T(B).

[0005] Differential charge pump 100 charges or discharges capacitor 110 in response to binary control signals UP and DN. Switches S(A) and S(D) are configured to turn on only when

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signal UP is asserted HIGH. Meanwhile, switches S(C) and S(B) are configured to turn on only when signal DN is asserted HIGH.

[0006] Thus, when signal UP is asserted and signal DN is deasserted, switches S(A) and S(D) are on (closed) and switches S(B) and S(C) are off (open). As a result, current flows through current sources CS(A) and CS(D) while current sources CS(B) and CS(C) are inactive. The current sourced by current source CS(A) charges the plate of capacitor 110 connected to terminal T(A) (i.e., plate 110(A)), while the current sunk by current source CS(D) drains charge from the plate of capacitor 110 connected to terminal T(B) (i.e., plate 110(B)). This charging of plate 110(A) and discharging of plate 110(B) increases output voltage VDIFF.

[0007] Likewise, when signal DN is asserted and signal UP is deasserted, switches S(C) and S(B) are closed, while switches S(A) and S(D) are opened. In this case, current sources CS(A) and CS(D) are inactive, while current source CS(C) charges plate 110(B), while current source CS(B) discharges plate 110(A). The discharging of plate 110(A) and charging of plate 110(B) decreases voltage VDIFF. Thus, differential charge pump 100 increases voltage VDIFF in response to signal UP and decreases voltage VDIFF in response to signal DN.

[0008] When differential charge pump 100 is first used, it is generally desirable that plates 110(A) and 110(B) both be at a particular "common mode" voltage. This ensures that the starting output voltage VDIFF is equal to zero. Also, by sizing the common mode voltage to be halfway between supply voltage VDD and ground (i.e., $VDD/2$), the allowable positive and negative changes in output voltage VDIFF can be maximized.

[0009] Unfortunately, when signals UP and DN are the same (i.e., both HIGH or both LOW, the voltage VDIFF across capacitor 110 will remain at whatever voltage was present when control

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branches B(A) and B(B) were last active. Consequently, each time differential charge pump 100 is used, plates 110(A) and 110(B) must be charged or discharged until they are both at the desired common mode voltage and output voltage VDIFF is set equal to zero. This "calibration" requirement can significantly increase the startup time for any circuit that incorporates differential charge pump 100.

[0010] In addition, differential charge pump 100 can also experience a dead zone if the corresponding switches (e.g., switches S(A) and S(D) or switches S(C) and S(B)) don't close at the same time, for example, due to propagation delays. In such circumstances, the terminal associated with the opened switch would be tri-stated, thereby creating a spurious reading of voltage VDIFF.

[0011] Accordingly, it is desirable to provide a differential charge pump that maintains a known common-mode voltage and has no dead zone.

SUMMARY OF THE INVENTION

[0012] The invention provides a differential charge pump that includes common mode circuitry for supplying a common mode voltage to the plates of a charging capacitor in the differential charge pump. The common mode circuitry includes a first common mode branch for applying a common mode voltage to a first plate of a charging capacitor, a second common mode branch for applying the common mode voltage to a second plate of the charging capacitor, and a biasing branch for controlling the operation of the first common mode branch and the second common mode branch.

[0013] According to an embodiment of the invention, the biasing branch includes a first bias pseudo-switch (constant-on switch), a reference transistor, a bias current transistor, and

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a second bias pseudo-switch, which are serially connected between supply voltage VDD and ground. The bias current transistor regulates the current flow through the biasing branch so that it is equal to a desired bias current. Meanwhile, the gate voltage of the reference transistor is adjusted until the drain voltage provided by the reference transistor is equal to a desired common mode voltage.

[0014] The first common mode branch includes a first pseudo-switch, a first transistor, a second transistor, and a second pseudo-switch, which are serially connected between supply voltage VDD and ground. The second common mode branch includes a third pseudo-switch, a third transistor, a fourth transistor, and a fourth pseudo-switch, which are serially connected between supply voltage VDD and ground. The first plate of the charging capacitor is connected to the junction between the first transistor and the second transistor, and the second plate of the charging capacitor is connected to the junction between the first transistor and the second transistor.

[0015] The second transistor and the fourth transistor are gate-coupled to the bias current transistor, so that the bias current flowing through the biasing branch is mirrored through the first and second common mode branches. Meanwhile, the first transistor and the third transistor are gate-coupled to the reference transistor. Because the first transistor and the third transistor receive the same gate voltage as the reference transistor (and the same bias current flows through the first transistor and the second transistor), the first transistor and the third transistor attempt to drive their drain voltages to the same level as the drain voltage of the common mode transistor (i.e., the desired common mode voltage). As a result, when not being charged or discharged in response to differential input signals, the plates of the charging capacitor

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are driven towards the common mode voltage by the common mode branches.

[0016] These and other aspects of the invention will be more fully understood in view of the following description of the exemplary embodiments and the drawings thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] Fig. 1 is a schematic diagram of a conventional differential charge pump.

[0018] Fig. 2A is a schematic diagram of a differential charge pump in accordance with an embodiment of the invention.

[0019] Fig. 2B is a schematic diagram of a capacitive structure that can be included in the differential charge pump of Fig. 2A.

[0020] Fig. 3 is a schematic diagram of a differential charge pump in accordance with another embodiment of the invention.

DETAILED DESCRIPTION

[0021] Fig. 2A shows a differential charge pump 200 in accordance with an embodiment of the invention. As described below, differential charge pump 200 includes both control branches and common mode branches. The control branches provide charging control during dynamic operations (i.e., when the two digital control signals to differential charge pump 200 are not the same). Meanwhile, the common mode branches provide a predetermined common mode voltage to the capacitor(s) during common mode operations (i.e., when the digital control signals are the same - both logic HIGH or both logic LOW), thereby beneficially eliminating the need for pre-use calibrations and preventing dead zones.

[0022] As depicted in Fig. 2A, differential charge pump 200 includes: switches S1, S2, S3, S4; pseudo-switches PS5, PS6,

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PS7, PS8, PS9, and PS10; current sources CS1, CS2, CS3, and CS4; PMOS transistors P1, P2, and P3; NMOS transistors N1, N2, N3; a capacitive structure 210; a voltage control circuit 220; and a current control circuit 230.

[0023] Switch S1, current source CS1, current source CS3, and switch S3 are serially connected between a upper supply voltage VDD and lower supply voltage VSS (e.g., ground) to form a first control branch B(C1). Switch S2, current source CS2, current source CS4, and switch S4 are serially connected between upper supply voltage VDD and lower supply voltage VSS to form a second control branch B(C2).

[0024] Capacitive structure 210 is connected between a first output terminal T(1) at the junction between current sources CS1 and CS2 and a second output terminal T(2) at the junction between current sources CS2 and CS4. Therefore, a differential output voltage VDIFF across capacitive structure 210 can be read via terminals T(1) and T(2).

[0025] For explanatory purposes, the operation of differential charge pump 300 is described with respect to a single charging capacitor 211 in capacitive structure 210. Capacitor 211 includes a first plate 211(1) connected to output terminal T(1) and a second plate 211(2) connected to output terminal T(2). First plate 211(1) and second plate 211(2) are separated by a dielectric layer (not shown). However, according to various other embodiments of the invention, capacitive structure 210 can include any number of capacitors. Note also that, according to various other embodiments of the invention, plates 211(1) and 211(2) can be connected to output terminals T(1) and T(2), respectively, by additional components, such as resistors or pass gates.

[0026] For example, Fig. 2B shows a capacitive structure 210 according to another embodiment of the invention. Capacitive

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structure 210 in Fig. 2B includes capacitors 211 and 211 connected in parallel. Capacitor 211 includes plates 211(1) and 211(2), which are connected to nodes N1 and N2, respectively. Capacitor 212 includes plates 212(1) and 212(2), which are connected to nodes N1 and N2, respectively. By forming plates 211(1) and 212(2) in a first metal layer and by forming plates 211(2) and 212(1) in a second metal layer, parasitic capacitance effects (e.g., between the first metal layer and the substrate) can be minimized.

[0027] Returning to Fig. 2A, the behavior of control branches B(C1) and B(C2) is controlled by a pair of digital control signals UP and DN. Signal UP turns on (closes) switches S1 and S4, while signal DN turns on switches S2 and S3. Therefore, because current source CS1 is coupled between upper supply voltage VDD and plate 211(1) by switch S1, and because current source CS4 is coupled between plate 211(2) and lower supply voltage VSS by switch S4, when signal UP is asserted, capacitor 211 is charged by a current flowing between current source CS1 and current source CS4. Similarly, because current source CS2 is coupled between upper supply voltage VDD and plate 211(2) by switch S2, and because current source CS3 is coupled between plate 211(1) and lower supply voltage VSS by switch S3, when signal DN is asserted, capacitor 211 is charged by a current flowing between current source CS2 and current source CS3. Therefore, when signal UP is asserted while signal DN is deasserted, the value of output voltage VDIFF is increased, and when signal UP is deasserted while signal DN is asserted, the value of output voltage VDIFF is decreased.

[0028] In this manner, when signal UP is asserted while signal DN is deasserted, the value of output voltage VDIFF is increased, and when signal UP is deasserted while signal DN is asserted, the value of output voltage VDIFF is decreased. Note

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that for explanatory purposes, signals UP and DN will be considered "asserted" when in a logic HIGH state, although the invention could just as well operate in response to control signals that are asserted to a logic LOW state.

[0029] According to an embodiment of the invention, switch S1, current source CS1, current source CS3, and switch S3 are matched to switch S2, current source CS2, current source CS4, and switch S4, respectively, thereby ensuring that the charging and discharging rates for capacitive structure 210 are substantially equal. Note that "matched" devices are devices that are configured to have substantially similar performance characteristics, typically through similar sizing and positioning.

[0030] In this manner, control branches B(C1) and B(C2) manage differential charge pump 200 during dynamic operations. However, as noted above, operation of differential charge pump 200 includes both dynamic operations (i.e., signals UP and DN different) and common mode operations (i.e., signals UP and DN the same). Therefore, to provide control over output voltage VDIFF during common mode operations, differential charge pump 200 further includes common mode branches B(M1) and B(M2), and a biasing branch B(B1).

[0031] Common mode branch B(M1) is formed by pseudo-switch PS6, PMOS transistor P2, NMOS transistor N2, and pseudo-switch PS9, which are serially connected between upper supply voltage VDD and lower supply voltage VSS. Common mode branch B(M2) is formed by pseudo-switch PS7, PMOS transistor P3, NMOS transistor N3, and pseudo-switch PS10, which are also serially connected between upper supply voltage VDD and lower supply voltage VSS. Pseudo-switches PS6, PS7, PS9, and PS10 are all constant-on (i.e., always closed) switches.

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[0032] PMOS transistor P2 is also coupled between upper supply voltage VDD and output terminal T(1) (by constant-on switch S1, while PMOS transistor P3 is coupled between upper supply voltage VDD and output terminal T(2) (by constant-on switch S2). Therefore, capacitive structure 210 is not only connected across control branches B(C1) and B(C2), but is also connected across common mode branches B(M1) and B(M2).

Consequently, common mode branches B(M1) and B(M2) can also adjust the voltage across capacitive structure 210 (and hence, can adjust differential output voltage VDIFF).

[0033] Biasing branch B(B1) is formed by (constant-on) pseudo-switch PS5, PMOS transistor P1, NMOS transistor N1, and (constant-on) pseudo-switch PS8, which are serially connected between upper supply voltage VDD and lower supply voltage VSS. Just as in common mode branches B(M1) and B(M2), pseudo-switches PS5 and PS8 are constant-on switches.

[0034] Biasing branch B(B1) controls the behavior and operation of common mode branches B(M1) and B(M2). Biasing branch B(B1) itself is controlled by current control circuit 230 and voltage control circuit 220, which impose a set of current and voltage parameters onto biasing branch B(B1). The operation of current control circuit 230 and voltage control circuit 220 is described below in detail.

[0035] Current control circuit 230 includes circuitry to force transistor N1 in biasing branch B(B1) to provide a desired current flow through biasing branch B(B1). According to an embodiment of the invention, current control circuit 230 includes an NMOS transistor N4 and a (constant-on) pseudo-switch PS11. NMOS transistor N4 is gate-drain coupled and connected to lower supply voltage VSS by pseudo-switch PS11. NMOS transistor N1 in biasing branch B(B1) is gate-coupled to transistor N4 in a current mirror configuration.

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[0036] Thus, an input bias current I_{BIAS} that is supplied to the drain of transistor N4 is mirrored by transistor N1 through biasing branch B(B1). Then, because the gates of NMOS transistors N2 and N3 in common mode branches B(M1) and B(M2), respectively, are connected to the gate of transistor N1, transistors N2 and N3 act as current sources that mirror bias current I_{BIAS} through common mode branches B(M1) and B(M2), respectively.

[0037] Meanwhile, voltage control circuit 220 includes circuitry to cause transistor P1 in biasing branch B(B1) to provide a desired output - i.e., a particular voltage level at its drain. (Note that if transistor P1 were an NMOS transistor, its output would appear at its source.) According to an embodiment of the invention, voltage control circuit 220 includes an operational amplifier (op-amp) 221. The output of op-amp 221 is connected to the gate of PMOS transistor P1, while the non-inverting input of op-amp 221 is connected to the drain of PMOS transistor P1.

[0038] Thus, an input voltage V_{IN} applied to the inverting input of op-amp 221 causes op-amp 221 to adjust the gate voltage of PMOS transistor P1 until the voltage at the drain of transistor P1 is equal to input voltage V_{IN} . Then, because the gates of PMOS transistors P2 and P3 in common mode branches B(M1) and B(M2), respectively, are connected to the gate of transistor P1, transistors P2 and P3 receive the same gate voltage received by transistor P1 from op-amp 221.

[0039] Since the gate voltage and current through transistor P2 matches the gate voltage and current through transistor P1, the drain voltage of transistor P2 is driven to the same level as the source voltage of transistor P1 (i.e., to voltage V_{IN}). Similarly, because the gate voltage and current through transistor P3 matches the gate voltage and current through

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transistor P1, the drain voltage of transistor P3 is also driven to voltage V_{IN} .

[0040] In this manner, common mode branches B(M1) and B(M2) provide voltage V_{IN} to plates 211(1) and 211(2), respectively, of capacitor 211, so that voltage V_{IN} represents the common mode voltage of differential charge pump 200. By providing this "always on" common mode voltage to capacitor 211, common mode branches B(M1) and B(M2) also eliminate any dead zone that could otherwise arise due to mistiming between switches S1-S4.

[0041] Note that, if voltage V_{DIFF} is not equal to zero when control branches B(C1) and B(C2) are both inactive, common mode branches B(M1) and B(M2) will charge or discharge plates 211(1) and 211(2) as necessary to bring them both to voltage V_{IN} (and set voltage V_{DIFF} equal to zero). For example, if plate 211(1) has a higher voltage than voltage V_{IN} , the voltage across transistor P2 is decreased, thereby decreasing the current sourced by transistor P2. However, transistor N2 still attempts to sink a current equal to current I_{BIAS} . Therefore, the charge stored on plate 211(1) provides this extra current flow until the voltage on plate 211(1) is reduced back to voltage V_{IN} and the current sourced by transistor P2 is the same as the current sunk by transistor N3. Similarly, if plate 211(1) has a lower voltage than voltage V_{IN} , the voltage across transistor P2 is increased, and the resulting excess current sourced by transistor P2 charges plate 211(1) until the voltage on plate 211(1) reaches voltage V_{IN} .

[0042] According to an embodiment of the invention, input voltage V_{IN} can be set equal to half of upper supply voltage V_{DD} (i.e., $V_{DD}/2$), thereby maximizing the useful range of output voltage V_{DIFF} . A common mode voltage equal to half of the supply voltage ensures that during dynamic operations, capacitor plate 211(1) is always charging while capacitor plate 211(2) is

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discharging, and vice versa. Note, however, that according to various other embodiments of the invention, input voltage V_{IN} can be set equal to any desired voltage level.

[0043] Note that differential charge pump 200 is depicted and described using an exemplary combination of NMOS transistors (i.e., N1-N4) and PMOS transistors (i.e., P1-P3). According to various other embodiments of the invention, similar functionality could be provided using devices having other conductivity types.

[0044] For example, NMOS transistor N4 could be replaced with a gate-drain coupled PMOS transistor, which in turn would be gate-coupled to three PMOS transistors that replace and NMOS transistors N1-N3. Similarly, transistor P1 could be replaced with an NMOS transistor having its drain connected to the inverting input of op-amp 221, while transistors P2 and P3 could be replaced with NMOS transistors, with the drains of those transistors being connected to plates 211(1) and 211(2), respectively.

[0045] According to another embodiment of the invention, the accuracy of the common mode voltage provided by common mode branches B(M1) and B(M2) can be optimized by matching transistors P1, P2, and P3, and by matching transistors N1, N2, and N3. According to another embodiment of the invention, additional increases in common mode voltage accuracy can be achieved if switches PS5, PS6, and PS7 are matched, and switches PS8, PS9, and PS10 are matched.

[0046] According to another embodiment of the invention, common mode branches B(M1) and B(M2) are configured to have performance characteristics similar to control branches B(C1) and B(C2), respectively. Specifically, pseudo-switch PS6, PMOS transistor P2, NMOS transistor N2, and pseudo-switch PS9 in common mode branch B(M1) are matched to switch S1, current

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source CS1, current source CS3, and switch S3, respectively, in control branch B(C1). Similarly, pseudo-switch PS7, PMOS transistor P3, NMOS transistor N3, and pseudo-switch PS10 in common mode branch B(M2) are matched to switch S2, current source CS2, current source CS4, and switch S4, respectively, in control branch B(C2).

[0047] Matching components in this manner ensures that common mode branches B(M1) and B(M2) are not overwhelmed by control branches B(C1) and B(C2), and vice versa. In other words, the current flows through common mode branches B(M1) and B(M2) are large enough to restore the plates of capacitive structure 210 to their nominal common mode voltage in a reasonable time, but not so large that they excessively dampen the charging and discharging effects of control branches B(C1) and B(C2).

[0048] For example, Fig. 3 shows a schematic diagram of a differential charge pump 300 according to an embodiment of the invention. Differential charge pump 300 is substantially similar to differential charge pump 200 shown in Fig. 2A, with switches S1 and S2 implemented by PMOS transistors P4 and P5, respectively; pseudo-switches PS5, PS6, and PS7 implemented by PMOS transistors P6, P7, and P8, respectively; switches S3 and S4 implemented by NMOS transistors N5 and N6, respectively; pseudo-switches PS8, PS9, PS10, and PS11 implemented by NMOS transistors N7, N8, N9, and N10, respectively; current sources CS1 and CS2 implemented by PMOS transistors P9 and P10, respectively; and current sources CS3 and CS4 implemented by NMOS transistors N11 and N12, respectively.

[0049] The transistors in differential charge pump 300 that replace the switches and current sources of differential charge pump 200 provide the same functionality (described above) as those switches and current sources. For example, PMOS transistors P6-P8 are all gate-coupled to lower supply voltage

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VSS, and therefore behave as constant-on switches. Similarly, NMOS transistors N7-N10 are all gate-coupled to upper supply voltage VDD, and therefore also behave as constant-on switches. Therefore, the operation of differential charge pump 300 is substantially similar to that of differential charge pump 200.

[0050] For example, just as described with respect to Fig. 2A, bias current I_BIAS supplied to transistor N4 is mirrored by transistor N1 into biasing branch B(B1), while input voltage V_IN provided to the inverting input terminal of op-amp 221 adjusts that gate voltage of transistor P1 until the drain voltage of transistor P1 is equal to voltage V_IN. Transistors N2 and N3 (gate-coupled to transistor N1) mirror current I_BIAS through common mode branches B(M1) and B(M2), respectively, so that the drain voltages of transistors P2 and P3 (gate-coupled to transistor P1) provide a common mode voltage V_IN to capacitive structure 210.

[0051] Due to the nature of semiconductor materials, a fully-on PMOS transistor exhibits a minimal voltage drop when coupled to a high voltage (such as upper supply voltage VDD), while a fully-on NMOS transistor exhibits a minimal voltage drop when coupled to a low voltage (such as lower supply voltage VSS). Therefore, by implementing the switches to voltage VDD using PMOS transistors (i.e., PMOS transistors P4-P8) and by implementing the switches to lower supply voltage VSS using NMOS transistors (i.e., NMOS transistors N5-N10), the range of output voltage VDIFF provided by differential charge pump 300 can be maximized. Note, however, that according to various other embodiments of the invention, the switches in differential charge pump 300 could be implemented using devices having any combination of conductivity types (e.g., all P-type transistors or all N-type transistors).

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[0052] To provide the appropriate charge pump action in response to control signals UP and DN, PMOS transistor P4 and NMOS transistor N6 must turn on in response to signal UP, while PMOS transistor P5 and NMOS transistor N5 must turn on in response to signal DN. Therefore, NMOS transistors N6 and N5 must receive the complements of the signals provided to PMOS transistors P4 and P5, respectively. According to an embodiment of the invention, inverters could be placed at the gates of PMOS transistors P4 and P5, or at the gates of NMOS transistors N5 and N6, depending on the nature of signals UP and DN.

[0053] For example, if signals UP and DN are raised to logic HIGH levels when asserted, inverters could be placed at the gates of PMOS transistors P4 and N5. Then, the assertion of signal UP would result in a logic LOW being provided at the gate of PMOS transistor P4 and a logic HIGH being provided at the gate of NMOS transistor N6, and the assertion of a signal DN would result in a logic LOW being provided at the gate of PMOS transistor P5 and a logic HIGH being provided at the gate of NMOS transistor N5.

[0054] On the other hand, if signals UP and DN are placed at logic LOW levels when asserted, inverters could be placed at the gates of NMOS transistors N5 and N6. Then, the assertion of signal UP would still result in a logic LOW being provided at the gate of PMOS transistor P4 and a logic HIGH being provided at the gate of NMOS transistor N6, and the assertion of a signal DN would still result in a logic LOW being provided at the gate of PMOS transistor P5 and a logic HIGH being provided at the gate of NMOS transistor N5.

[0055] Because the gates of transistors P9 and P10 are connected to the gate of transistor P1, which is held at a particular voltage by op-amp 221, transistors P9 and P10 are current sources for current I_BIAS (i.e., they can source

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currents equal to current I_{BIAS}). Likewise, because the gates of transistors N11 and N12 are connected to the gate of transistor N1, transistors N11 and N12 are also current sources for current I_{BIAS} (i.e., they can sink currents equal to current I_{BIAS}).

[0056] Therefore, when transistors P4 and N6 are on and transistors P5 and N5 are off (i.e., signal UP asserted and signal DN deasserted), the current sourced by transistor P9 charges plate 211(1) of capacitor 211, while the current sunk by transistor N12 discharges plate 211(2). When transistors P4 and N6 are off and transistors P5 and N5 are on (i.e., signal UP deasserted and signal DN asserted), the current sunk by transistor N11 discharges plate 211(1) while the current sourced by transistor P10 charges plate 211(2).

[0057] The various embodiments of the structures and methods of this invention that are described above are illustrative only of the principles of this invention and are not intended to limit the scope of the invention to the particular embodiments described. For example, while differential charge pump 300 in Fig. 3 is depicted as a CMOS circuit, according to various other embodiments of the invention, a straight NMOS or PMOS process, or even a bipolar process, could be used to implement the circuit. Also, the constant-on pseudo-switches PS5-PS11 of differential charge pump 200 in Fig. 2A could be replaced with controllable switches that allow the common mode capability of differential charge pump 200 to be selectively enabled or disabled. Thus, the invention is limited only by the following claims and their equivalents.